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Introducing a new technique in wire electrical discharge turning and evaluating ultrasonic vibration on material removal rate

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Abstract

Wire electrical discharge turning (WEDT) is suitable for machining of precise cylindrical forms on hard and difficult-to-cut materials. In WEDT electrical discharge takes place between the traveling wire and the rotating workpiece to be machined. However, in many cases the machining efficiency of WEDT is considered to be rather low. One of the methods to enlarge the application envelope of WEDT and to improve its machining performance on difficult-to-machine materials is introduction of ultrasonic vibration to the wire electrode. An investigation has been made to combine ultrasonic vibration and wire electrical discharge turning. Design of a submerged, precise, flexible and corrosion-resistant rotary spindle is introduced. The spindle was mounted on a five-axis wire EDM machine to rotate the workpiece in order to generate free form cylindrical geometries. An auxiliary device which produces ultrasonic vibration was installed between the two wire-guides. The ultrasonic system consists of an ultrasonic generator, a transducer and a wire holder. When the wire is being driven, the transducer together with the wire holder vibrate under the resonance condition. Material removal rate (MRR) indicates efficiency and cost-effectiveness of the process. Experimental results show that wire vibration induced by ultrasonic action has a significant effect on material removal rate. This study has been to evaluate the influence of four design factors: power, pulse off time, spindle rotational speed and ultrasonic vibration over material removal rate. This has been done by means of design of experiments (DOE) technique. Analysis of variance (ANOVA) was used to determine significant effective factors.

Keywords: WEDT; Ultrasonic vibration; Material remival rate;Statistical analysis

1. Introduction

Electrical discharge machining (EDM) is used for cutting of electrically conductive materials. It is suitable for heavy machining as well as manufacturing delicate parts since the machining energy involved during the process can be very low compared with other conventional machining methods. Masuzawa et al. [1] reported using wire EDM to machine cylindrical parts for manufacturing small pins. Miniature electrodes and micro-structures were fabricated successfully with this technique [2]. Weingärtner et al. [3] presented on machine wire electrical discharge dressing method using a special wire guide. By using the designed wire guide system, higher material removal rates and better dressing accuracy were achieved. However, in many cases the machining efficiency of EDM is considered to be rather low. One of the methods to enlarge the application envelope of EDM and to improve its machining performance on difficult-to-machine materials is introduction of ultrasonic vibration to the electrode [4]. Indeed, the study of the effects of ultrasonic vibration of the electrode on EDM has been undertaken since the mid-80s, and some promising results have been obtained [5]. Abdullah and Shabgard [6] observed that in die-sinking EDM application of ultrasonic vibration significantly reduces arcing and open circuit pulses, and the stability of the process had a remarkable improvement. Guo et al. [7] found that there exists an optimum relationship between the vibration amplitude of the wire and the discharge energy in ultrasonic-assisted

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wire EDM, by which the highest cutting rate and the best machined surface quality, can be obtained. In addition, ultrasonic vibration reduced the residual tensile stress of the machined surface. Wire electrical discharge turning (WEDT) is suitable for machining of precise cylindrical forms on hard and difficult-to-cut materials. Mohammadi et al. [8] investigated the turning by wire electrical discharge machining to evaluate the effects of machining parameters on material removal rate. They found that power, voltage and servo have most significant effect and rotational speed, wire tension, wire speed and time-off have least significant effect on MRR. In wire electrical discharge turning (WEDT) electrical discharge takes place between the traveling wire and the rotating workpiece to be machined. In the developed WEDT in this research, wire guiding block is employed to avoid vibration and deviation of the wire, in order to maintain the gap distance between the workpiece electrode and the wire throughout the WEDT process. In the present work a new ultrasonic assisted wire electrical discharge turning has been developed in which ultrasonic vibrations are applied to the wire passing through wire guides. It has shown a remarkable improvement in material removal rate.

2. Experimental set up

2.1. . Spindle design

The developed wire electrical discharge turning using ultrasonic vibration is shown in Fig. 1. The rotating workpiece is driven by a spindle submerged in a tank of deionized water. A precise submerged spindle is the key sub-system of the experiments. A DC motor coupled to timing belt is used to transmit the motion to the collet holder of spindle. A special sealing is used to prevent the EDM debris entering the bearing housing.

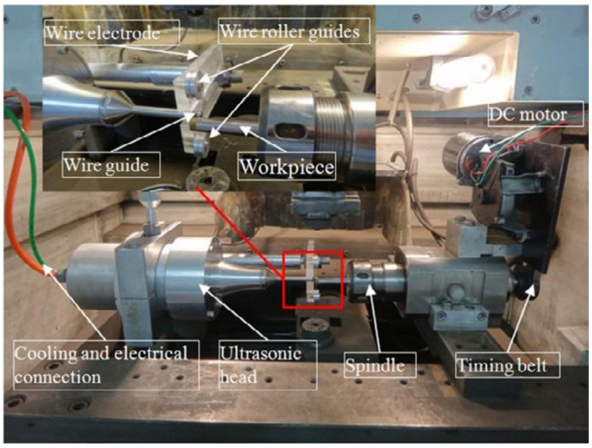

Fig. 1 Spindle and ultrasonic head in five-axis WEDM machine

Spindle run out error is an important parameter that can affect the maximum material removal rate of turning wire EDM parts. The spindle run out error affects the consistency of the gap condition. Run out at a distance of 50 mm from the face of collet must not exceed 10 µm.

2.2. Vibration device

A round stainless steel bar with a WC head (wire holder) which transmits ultrasonic vibration from the ultrasonic transducer to the wire is installed between the two wire guides. The WC head at the end of this bar has a 0.1 mm depth slot for guiding and vibrating the wire.

The ultrasonic system consists of an ultrasonic generator, a transducer, a conical concentrator and a wire holder. The electrical generator is capable of producing ultrasonic waves with a maximum output power of 1.2 KW. The transducer vibrates the wire holder in the direction along the rotational axis of the workpiece (Fig. 1). The wire guide (holder) is the most important component in this equipment. Its head is made of a WC alloy wheel-shaped, and a 0.1 mm groove is cut along the circumference of the guide for holding the travelling wire electrode. A schematic shape of the wire guide and the workpiece is shown in Fig. 2. During machining, the wire electrode is travelling through the groove in the wire holder. Vibration of the wire is amplified by the concentrator. The wire vibration amplitude can be adjusted by the output power of the ultrasonic power supply. When the wire is being driven, the transducer together with the wire holder vibrate under resonance condition in longitudinal direction.

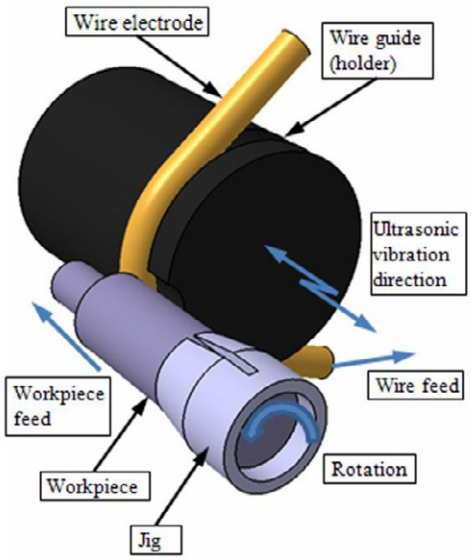

Fig. 2 Positioning of the wire guide and workpiece

3. Design of experiments and data analysis

In this research, all experiments were conducted on an ONA R250 wire EDM machine. A rotary axis and ultrasonic head were added to the conventional five-axis wire EDM machine in order to produce cylindrical forms. The experiments were aimed at considering the effects of several controllable factors on material removal rate (MRR). Theoretical Eq. 1 can be derived to describe MRR:

$$MRR = \pi.\left(R^2 - r^2\right)v_f \quad (1)$$

Where R is the original radius of the workpiece, r is the new reduced radius of the workpiece after machining, and vf is the machining cutting speed or feed rate. According to primary tests accomplished on HSS specimens by the authors using ONA Aricut R250 technology manual and user's guide, the erosion parameters in the experiments are as given in Table 1.

Table 1. Set of parameters used on material removal rate experiments on ONA R250 wire EDM

Parameter	Value
Power (for each power level there is a corresponding average current between the wire and the workpiece, A)	3, 6, 10
Time-off (µs)	4, 7, 12
Rotational speed (RPM)	16, 45
Ultrasonic vibration	0 (OFF), 1 (ON)
Output power of ultrasonic transducer (W)	200
Maximum cutting feed rate (mm/min)	2
Depth of cut (mm)	0.06
Diameter of specimens (mm)	6
Workpiece hardness (HRC)	64±2
Material	HSS
Machining length (mm)	6.5
Wire material	Brass
Wire diameter (mm)	0.25
Open arc voltage (V)	120
Servo (V)	20

For more details about the definition of machine parameters, refer to "ONA TECHNOLOGY, ARICUT-ARION manual"

In order to investigate the effect of ultrasonic vibration on the performance of process, initial tests at different output powers of transducer were performed and 200 W was chosen the best possible choice. For ultrasonic output powers of less than this value, the ultrasonic effect is negligible. Higher powers than this cause short circuit and wire breakage and the process is interrupted. Therefore, the optimum output power of ultrasonic transducer is 200 W and in this power, maximum amplitude of vibration is 10 µm.

One of the most used techniques to design experiments is full factorial design, which consists of experimenting with all the possible combinations of variables and levels. The important strength of full factorial design of experiments is the potential to build models and to gradually increase the complexity of the models if this is needed. If the number of the design factors' level is different, a kind of full factorial design, mixed level design, is used. These mixed level factorial designs are among the most widely used types of designs for process design and process improvement [9].

In this research, a mixed level design of $3^2 \times 2^2$ was applied for experimentation. Subsequently, 36 experiments were conducted with the parameter levels. The resolution of this factorial design allows us to estimate all the main effects and factor interactions in this study. The experiments were performed in random order using a randomization table. MINITAB—a statistical software—was employed to design the tests and analyze the experimental findings. Analysis of variance (ANOVA) has been often employed, since it covers the shortcomings of graphical assessment. Two of these shortcomings are inaccuracy in the inferences made and that the inferences are only comparatively valid. Before conducting ANOVA, the assumptions used during this analysis are verified as follows:

It is clear from the normal probability plot of residuals (Fig. 3 (a)) that the points generally form a straight line and also the p-value calculated based on the Anderson-Darling (AD) statistic is higher than α-level of confidence (0.05), so it is concluded that the error (residual) is normal. Residuals-versus-fitted-values plot (Fig. 3 (b)) shows a random pattern of residuals on both sides of the zero line. There is not any recognizable pattern in the residual plot and this proves the constancy of variance [9].

In the above discussion, ANOVA assumptions (error normality, error independency, variance constancy) are proved to be valid, so ANOVA can be performed and the inferences made based on its table will be valid. Table 2 is ANOVA table for MRR. As it shows, the assumptions are proved not to be violated through this experimentation; it can be relying on ANOVA results which are listed below. Confidence level is chosen to be 95% in this study. So the p-values which are less than 0.05 indicate that null hypothesis should be rejected, and thus the effect of the respective factor is significant. It can be seen from Table 2 that power and ultrasonic vibration ($p = 0.000$) have the most significant impact on MRR. Rotational speed ($p = 0.002$) exhibits significant effect on MRR as well. The effect of time-off (p = 0.003) is on the verge of significance, however, still seems to be significant. The interaction effects between time-off and rotational speed exhibits significant effect on MRR as well.

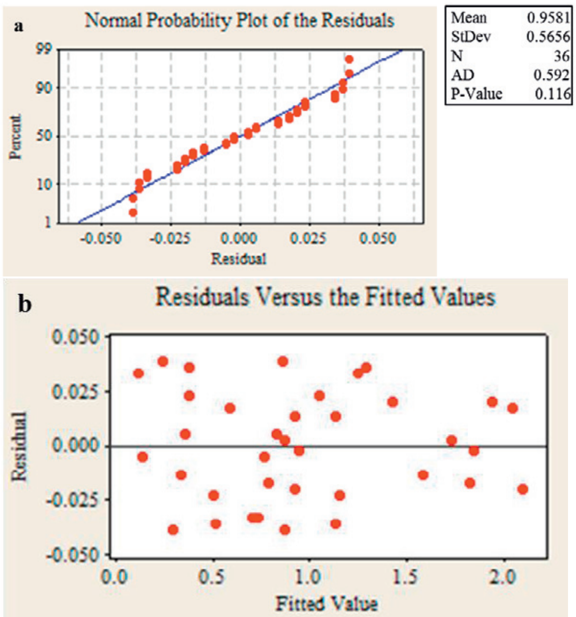

Fig. 3 (a) Normal probability, (b) Residuals versus fitted values plots

Table 2. Analysis of variance for MRR, using Adjusted SS for tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
P	2	4.27444	4.27444	2.13722	387.42	0.000
T	2	0.35524	0.35524	0.17762	32.20	0.003
R	1	0.29675	0.29675	0.29675	53.79	0.002
US	1	5.30024	5.30024	5.30024	960.80	0.000
P*T	4	0.01810	0.01810	0.00453	0.82	0.574
P*R	2	0.00737	0.00737	0.00369	0.67	0.562
P*US	2	0.27591	0.27591	0.13796	25.01	0.005
T*R	2	0.36988	0.36988	0.18494	33.53	0.003
T*US	2	0.01811	0.01811	0.00905	1.64	0.302
R*US	1	0.00050	0.00050	0.00050	0.09	0.778
P*T*R	4	0.08726	0.08726	0.02181	3.95	0.106
P*T*US	4	0.09152	0.09152	0.02288	4.15	0.099
P*R*US	2	0.03031	0.03031	0.01515	2.75	0.178
T*R*US	2	0.05004	0.05004	0.02502	4.54	0.094
Error	4	0.02207	0.02207	0.00552		
Total	35	11.19774				

S = 0.0742732 R-Sq = 99.80% R-Sq(adj) = 98.28%

(P=Power, T=Time-off, R=Rotational speed, US=Ultrasonic vibration)

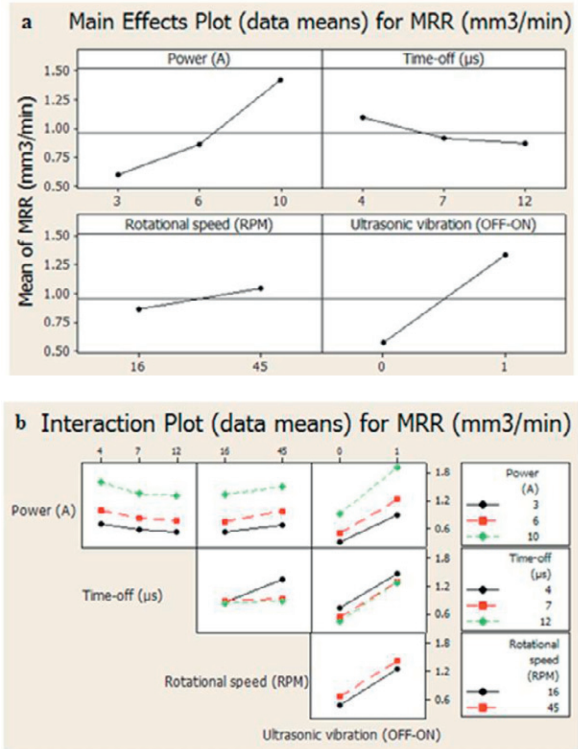

Fig. 4 (a) Main effects, (b) Interaction plots for MRR

The effects of interaction between power and ultrasonic vibration are on the verge of significance. The other interactions have no effect on MRR as it is indicated in Table 2. The R-Sq (R2) value indicates that the predictors explain 99.80% of the variance in MRR. The R-Sq (adj) (adjusted R2) is 98.28% which accounts for the number of predictors in the model. Both values indicate that the model fits the data well.

Fig. 4 (a and b) serve the purpose of graphical assessment and depict the plots of factor effects and interaction effects on changes of MRR, respectively. Fig. 4 (a) shows that power and ultrasonic vibration have the most significant effect on MRR. In addition, the power and ultrasonic vibration have direct proportion to MRR change; that is, by increasing power and applying ultrasonic vibration, MRR increases significantly. Also, it is indicated from Fig. 4 (a) that rotational speed and time-off have a significant effect on MRR furthermore, it is seen that pulse off time is reciprocally proportional to MRR.

4. Discussion

According to Fig. 4 (a), ultrasonic vibration has significant effect on MRR. MRR increase under application of ultrasonic vibration to the wire guide, is expected to be from reduction of friction between the wire and the wire guide, better flushing and dielectric circulation and creating material ejection from the molten crater under ultrasonic periodic suctions.

The sliding friction between contacting surfaces can be influenced by the application of ultrasonic vibration. The investigation on sliding friction of ultrasonic vibration both parallel and perpendicular to the sliding direction has been shown that significant reduction in sliding friction occurs duo to instantaneous changes in the vector of the force [10,11]. In another work [12], through the means of computational analysis carried out with the use of dynamic friction models, under the influence of forced longitudinal and/or tangential vibrations of high frequency, the reduction of the average friction force is reported. In this study, due to reduction of friction, the tensile stress on the wire is reduced and the wire breakage is less probable. Therefore, the process stability is increased with increased material removal rate.

The longitudinal ultrasonic vibration of the wire creates longitudinal compressive and rarefaction wave front, micro bubbles and intensive ejecting micro streams, which in turn aids very violent and accelerative mass transfer across the spark gap, acting as a pump, causing better debris suspension and evacuation from the gap and better dielectric fluid renewal.

Ultrasonically induced cavitation is defined as the formation, growth, and collapse of gaseous or vaporous bubbles under the influence of ultrasound [13]. This, in addition to high frequency suction action on the molten overheated crater under the plasma channel over the workpiece surface result in evacuation of the molten puddle which changing and influencing physics of material removal; that gives rise to more removal and less resolidified layer on the workpiece surface. [6,14,15]

4.1. Effect of ultrasonic vibration on MRR in different powers

Power parameter specifies the average electrical discharge current to the gap and MRR increases with increasing power (Fig. 4 (a)). In order to investigate the effect of ultrasonic vibration in finishing and roughing conditions, levels 3, 6 and 10 of power were selected. According to the manufacturer's manual, levels from 0 to 7 are used for finishing, while levels from 8 to 15 are used for roughing. Fig. 4 (b) shows that in both finishing and roughing conditions, the ultrasonic vibration affects MRR. Although in the roughing conditions (using high power) the ultrasonic vibration effect is more significant and it is due to further improvement of flushing conditions and cavitation. There is also a lower chance of wire breakage which may lead to MRR increase.

4.2. Effect of ultrasonic vibration on MRR in different time-offs

Time-off is used for cleaning accumulated material from the discharge gap and providing the channel with clean dielectric for the following discharges. A relationship between time-off and MRR is shown in Fig. 4 (a). A shorter dwell means less time between sparks, so that cutting is faster and MRR increases. If dwell is so short that the discharge gap cannot be properly cleaned, secondary discharges will occur with the material scattered in the channel, along with micro short circuits. In this case, ultrasonic vibration help to clean accumulated material from the discharge gap and the clean dielectric in the gap is prepared for the next spark. When the time between two cycles is higher, MRR decreases and by using ultrasonic vibration, cavitation may be formed and the MRR increases (Fig. 4 (b)).

4.3. Effect of ultrasonic vibration on MRR in different rotational speeds

Mohammadi et al. [8] and Janardhan and Samuel [16] point out that the relative speed affects erosion efficiency to a great extent, showing that the erosion material removal rate decreases by increasing relative speed. But in the developed WEDT, Wire guiding block is employed to avoid vibration and deviation of the wire. Therefore, in this process with increasing rotation speed, higher maximum material removal rates may be achieved, possibly due to non-vibration of the wire and better debris flushing condition as is shown in Fig. 4 (a). By using ultrasonic vibrations, at low and high rotational speeds, the MRR increases. The reason may be due to cavitation and improving flushing conditions (Fig. 4 (b)).

4.4. Effects of wire guide vibration on process stability and voltage pulse shape

In all experiments, it was found that the process stability is much higher when using ultrasonic vibrations. Looking at the discharge voltage pulse series, it is found that, most of the voltage pulses have successfully become normal spark type variations under ultrasonic effect. Fig. 5 shows the difference between gap voltage pulse shape under ultrasonic and without ultrasonic in different machining parameter settings.

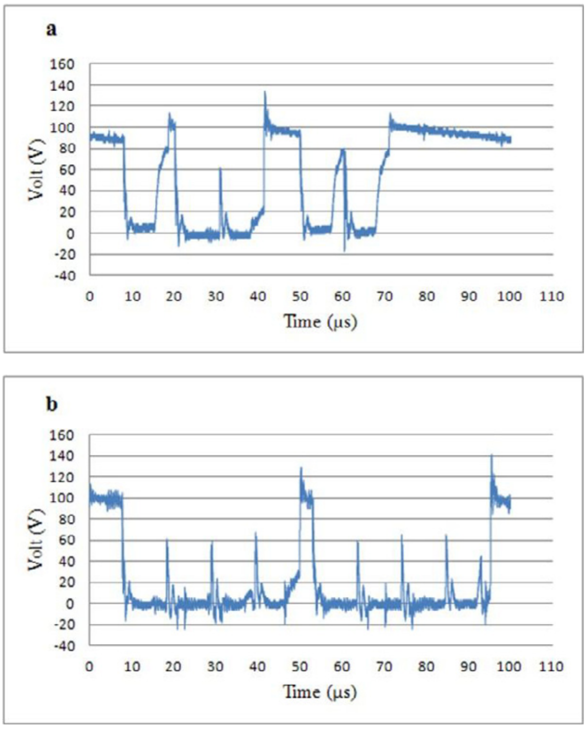

Fig. 5 Sample of the voltage-pulse series in (a) WEDT, (b) US/WEDT (power: 6 A, Time-off: 7 µs, Rotational speed: 45 RPM)

5. Conclusion

A new method of vibration transfer to the wire in ultrasonic assisted wire electrical discharge turning is proposed. A prototype system was built, and experiments were conducted and calculations were carried out for clarifying the characteristics of this method by obtaining effects on material removal rate (MRR). The following conclusions can be made:

1- The higher MRR gained by the employment of ultrasonic vibration is mainly attributed to reduction of friction between the wire and the wire guide that causing reduction of wire breakage, improvement in flushing and creation of suction on the molten material crater, resulting in a greater MRR.

2- The effects of ultrasonic vibration, discharges power, time-off and rotational speed on MRR are experimentally investigated. As the experimental results show, ultrasonic vibration has a significant effect on MRR in finishing and roughing conditions. In fact, in the roughing condition, the ultrasonic vibration effect is more significant. This can be attributed to less friction between the wire and the guide, further improvement of the flushing condition and better material suction.

3- The parameter levels that give the maximum MRR were determined. The ideal parameter settings to achieve maximum output, is when ultrasonic vibration is ON, power is 10 A; time-off is 4 µs and rotational speed is 45 RPM (for process conditions applied in this study). The achieved MRR with these parameters was 2.08026 mm^3/min.

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